

Gamma-ray bursts and Population III stars

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Abstract Gamma-ray bursts (GRBs) are ideal probes of the epoch of the first stars and galaxies. We review the recent theoretical understanding of the formation and evolution of the first (so-called Population III) stars, in light of their viability of providing GRB progenitors. We proceed to discuss possible unique observational signatures of such bursts, based on the current formation scenario of long GRBs. These include signatures related to the prompt emission mechanism, as well as to the afterglow radiation, where the surrounding intergalactic medium might imprint a telltale absorption spectrum. We emphasize important remaining uncertainties in our emerging theoretical framework.

Keywords Gamma-ray bursts · First Stars · Cosmology · Dark ages

1 Introduction

With recent progress in observational cosmology, one of the key frontiers is to understand how the first stars and galaxies ended the cosmic dark ages a few hundred million years after the Big Bang (Bromm et al. 2009; Loeb 2010). Prior to their emergence, the universe exhibited a simple state, devoid of complex structure, of any elements heavier than lithium, and of high-energy radiation fields. Within Λ CDM cosmology, the first stars, the so-called Population III (Pop III), are predicted to form at $z \sim 20 - 30$ in dark matter

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minihalos of mass $\sim 10^6 M_\odot$. The formation of the first bona-fide galaxies, being able to host long-lived stellar systems, may be delayed until more massive dark matter halos virialize (Bromm & Yoshida 2011). Once the first sources of light have appeared on the cosmic scene, the universe was rapidly transformed through the input of ionizing radiation (Barkana & Loeb 2007) and heavy chemical elements (Karlsson et al. 2013). The character of this fundamental transition, as well as the assembly process of the first galaxies, crucially depended on the feedback exerted by Pop III stars (Ciardi & Ferrara 2005). The feedback in turn is determined by the initial mass function (IMF) of the first stars (Bromm & Larson 2004; Glover 2005). Although important uncertainties remain, the key prediction is that the Pop III IMF is biased towards high mass, implying a top-heavy distribution (Bromm 2013). At least a fraction of the first stars could therefore have collapsed into massive black holes (BHs) at the end of their short lives, and thus provide viable gamma-ray burst (GRB) progenitors.

Upcoming facilities such as the James Webb Space Telescope (JWST), and the next generation of extremely-large telescopes on the ground (GMT, TMT, E-ELT) promise to open up a direct window into the first billion years of cosmic evolution (Gardner et al. 2006). Despite their exquisite sensitivity at near-IR wavelengths, even these observatories may not be able to directly probe the first stars, unless they formed in massive clusters (Pawlik et al. 2011), or were gravitationally lensed (Rydberg et al. 2013). The only opportunity to probe individual Pop III stars may be to catch them at the moment of their explosive death. This could involve extremely energetic supernova (SN) events, such as hypernovae or pair-instability SNe (Hummel et al. 2012; Pan et al. 2012; Whalen et al. 2013), or GRBs. The latter fate depends on whether Pop III stars could give rise to suitable collapsar progenitors, involving rapidly rotating massive stars (MacFadyen & Woosley 1999). Since Pop III stars are predicted to fulfill both requirements (see the discussion below), GRBs are expected to be prevalent at very high redshifts. Indeed, GRBs may play a key role in elucidating primordial star formation, as well as the properties of the early intergalactic medium (IGM), given their extreme intrinsic brightness, both of the prompt γ -ray emission, as well as that of the prolonged afterglow.

A number of features render GRBs ideal probes of the epoch of first light (Loeb 2010): *(i)* Traditional sources to observe the high- z universe, such as quasars and Lyman- α emitting galaxies, severely suffer from the effects of cosmological dimming. It was suggested, on the other hand, that GRB afterglows, if observed at a fixed time after the trigger, may exhibit nearly-flat infrared fluxes out to very high z (Ciardi & Loeb 2000). The argument behind this counter-intuitive effect was as follows: A fixed time interval in the observer frame translates into an increasingly early time in the source frame. Such earlier times in turn would sample the rapidly decaying GRB lightcurve at the moment of maximal brightness, thus compensating for the cosmological dimming (increasing luminosity distance). With the realization that such simple power-law decay may not be established until quite late after the trigger, this distance independence of the high- z burst flux now appears too optimistic.

(*ii*) In the hierarchical setting of cosmic structure formation, earlier times are dominated by lower-mass host systems. The massive hosts required for quasars and bright galaxies therefore are dying out at the highest redshifts (Morlock et al. 2011). GRBs, on the other hand, mark the death of individual stars, which can form even in very low-mass systems. (*iii*) Finally, Pop III GRBs would provide very clean background sources to probe the early IGM. Again reflecting the low masses of their hosts, any proximity effect should be much reduced, as ionized bubbles are confined to the immediate vicinity of the Pop III system; the IGM would thus largely remain unperturbed. In addition, since GRB afterglow spectra can be described as featureless, broken power-laws (Vreeswijk et al. 2004), any signature imprinted by absorption and emission events along a given line of sight can be easily discerned.

The outlook for GRB cosmology, therefore, is bright, provided that we can continue to fly wide-field γ -ray trigger instruments in space, beyond the end of the *Swift* satellite. We already have tantalizing examples of high-redshift bursts with the spectroscopically confirmed GRB 090423 at $z \simeq 8.2$ (Salvaterra et al. 2009; Tanvir et al. 2009), and the photometrically detected GRB 090429B at $z \simeq 9.4$ (Cucchiara et al. 2011). Future missions, such as SVOM (Paul et al. 2011), promise to fully unleash the potential of GRBs to probe the early universe. This review is organized as follows. In Section 2, we discuss the recent consensus on the formation of the first stars, with a particular focus on assessing their suitability as GRB progenitors. In Section 3, we continue by summarizing the key stellar evolution physics of these suggested Pop III progenitors. In Section 4, we discuss promising observational avenues to probe the signature of Pop III GRBs, and end with a brief outlook into the future in Section 5. In concluding, we would like to refer the reader to two recent reviews, one providing a comprehensive perspective on modern GRB astrophysics (Kumar & Zhang 2015), and the other a concise summary of the lessons from the *Swift* era for GRB cosmology (Salvaterra 2015).

2 Formation of Population III stars

The longstanding consensus view has been that the conditions in the early universe favored the formation of predominantly massive stars, such that the Pop III IMF was top-heavy (Abel et al. 2002; Bromm et al. 2002; Bromm & Larson 2004). This expectation rests on the much less efficient cooling in pure H/He gas, where the only viable cooling agent is molecular hydrogen. The primordial gas can therefore reach temperatures of only ~ 200 K, compared to the 10 K reached in dust-cooled molecular clouds in the present-day Milky Way. The correspondingly enhanced thermal pressure is reflected in a Jeans mass that is larger by one to two orders of magnitude in the Pop III case. Another element of this “standard model” of primordial star formation has been that the first stars formed typically in isolation, one per minihalo (Omukai & Nishi 1999).

In recent years, this traditional paradigm has been refined in important ways (Turk et al. 2009; Stacy et al. 2010; Clark et al. 2011; Greif et al. 2011,

2012). Supercomputing power, as well as algorithmic advances, now enable us to follow the protostellar collapse to densities, $n \sim 10^{22} \text{ cm}^{-3}$, where the initial hydrostatic core forms in the center of the cloud (Yoshida et al. 2008). Crucially, the computations can now also be extended into the main accretion phase (Omukai & Palla 2003). An important lesson has been that accretion is mediated through a near-Keplerian disk, similar to present-day star formation. The hot conditions in the surrounding cloud result in extremely large rates of infall onto the disk ($\dot{M} \propto T^{3/2}$); this rapid mass-loading drives the disk inevitably towards gravitational instability, such that a small multiple of Pop III protostars emerges, often dominated by a binary system. It is not yet possible to extend such ab-initio simulations all the way to the completion of the protostellar assembly process; the final mass of Pop III stars and their final IMF are thus still subject to considerable uncertainty. However, first attempts to carry out the radiation-hydrodynamical calculations required to treat the late accretion phase, where protostellar feedback tends to limit further infall, have confirmed the basic prediction: the first stars were typically massive, with masses of a few $\sim 10M_{\odot}$, although rarely very massive ($> 100M_{\odot}$), as previously thought, forming as a member of small multiple systems (McKee & Tan 2008; Hosokawa et al. 2011; Stacy et al. 2012). There are indications, though, that the Pop III mass could occasionally grow to $> 300M_{\odot}$, in cases of unusually weak protostellar feedback (Hirano et al. 2014; Susa et al. 2014).

Are Pop III stars suitable GRB progenitors? To successfully trigger a collapsar event, the leading contender for long-duration GRBs (Woosley 1993; MacFadyen et al. 2001), a number of conditions have to be met: a central BH has to form, a relativistic jet has to escape the stellar envelope before being quenched, and there has to be a sufficient degree of angular momentum close to the center, to delay the accretion of material onto the BH. These are quite stringent, and often difficult to fulfill simultaneously (Zhang & Fryer 2004; Petrovic et al. 2005; Belczynski et al. 2007).

The first requirement for a collapsar central GRB engine, the emergence of BH remnants, is fulfilled because of the top-heavy nature of the primordial IMF. The binary nature of Pop III stars may allow to meet the second requirement of providing an escape channel for the jet, if the binary is sufficiently close to allow for Roche-lobe overflow and a common-envelope phase, to expel the extended hydrogen (and helium?) envelope. This may be crucial to prevent the quenching of the relativistic jet, launched by the central engine (Bromm & Loeb 2006) (but see Suwa & Ioka 2011, and the discussion on this key point below). Simulations have begun to constrain the statistics of Pop III binaries, within a fully cosmological context (Stacy & Bromm 2013). The resulting distribution of semi-major axes is found to be quite broad, with a peak around $\sim 300 \text{ AU}$. Those simulations, however, cannot yet resolve the formation and evolution of tight binaries, due to the resolution limit of $\sim 20 \text{ AU}$. Such improved simulations would be required to probe the regime of contact binaries, where Roche-lobe overflow or common-envelope evolution could occur during the later red supergiant phase. It appears likely, though, that such tight binaries exist. A fraction of the sink particles that numerically repre-

sent Pop III stars in the simulations undergo mergers when they approach to within the resolution limit. With better resolution, some of those sinks/stars may well survive as tight binaries.

What about the additional requirement that the collapsar progenitor retains enough angular momentum? This question ties in with the rate of rotation of Pop III stars, where almost nothing is known yet. A first attempt to address this within a fully cosmological context has recently been carried out (Stacy et al. 2011, 2013), indicating that the first stars may have typically been very fast rotators, with surface rotation speeds of a few 10 percent of the break-up value. Such high rates of rotation would have important consequences for Pop III stellar evolution, possibly enabling strong mixing currents, and for the fate encountered at death (Yoon et al. 2006). Thus, it is plausible that all requirements for a collapsar central engine were in place in the early universe.

An important caveat here is that any effect of possible magnetic braking on the final stellar rotation rate has been neglected so far. Recent studies have argued that turbulent dynamo amplification in the primordial protostellar disks might rapidly build up dynamically significant magnetic fields (e.g., Schober et al. 2012). It is currently not clear whether such small-scale, tangled fields could be organized into larger scale arrangements. If they can, magnetic torques may be responsible for establishing Pop III stellar rotation rates similar to what is known for present-day O stars. Ongoing magneto-hydrodynamical simulations should soon help to clarify this key point.

3 Evolution of Pop III stars and GRBs

Metallicity is one of the prime factors that determine the evolution of massive stars. Many features of stellar evolution are therefore uniquely found with massive Pop III stars, compared to the case of metal-rich counterparts.

Massive stars on the main sequence in the nearby universe are powered by the CNO cycle. In the early universe, CNO elements are absent and core hydrogen burning starts with the pp chain. Because energy production by the pp-chain is too weak to maintain thermal equilibrium, a massive Pop III star initially undergoes thermal contraction until the central temperature becomes high enough for helium burning to produce carbon. The CNO cycle then becomes active with thus-produced carbon, and the structure of the star is adjusted accordingly until thermal equilibrium is reached. The main sequence evolution begins only thereafter (e.g., Marigo et al. 2001; Ekström et al. 2008; Yoon et al. 2012).

The evolution on the main sequence and in later stages is more critically affected by the lack of heavy elements. In metal-rich environments, massive star evolution is characterized by strong mass loss by radiation-driven winds, for which iron lines play a particularly important role (e.g., Puls et al. 2008). For massive Pop III stars, the radiation force resulting from hydrogen and

helium lines is too weak to drive a wind, and the predicted mass loss rate is extremely low (i.e., $\dot{M} \leq 10^{-14} M_{\odot} \text{ yr}^{-1}$; Krťicka & Kubát (2006)).

This has two important consequences. First, massive Pop III stars would not easily lose their initial angular momentum via mass loss. This implies that the evolution of massive Pop III stars could be dominated by the effects of rotation (Sects. 3.1 and 3.2). Second, even very massive stars ($M \gtrsim 100 M_{\odot}$) that are close to the Eddington limit would retain their hydrogen envelopes until the end of the evolution. This can produce very massive red supergiant stars (see Fig. 1), which are not found in the local universe. Metallicity effects also critically influence the condition for convection inside stars, which plays an important role in the final structure at the pre-collapse stage (Sect. 3.3). All of these effects are closely related to the properties of Pop III GRB progenitors, as discussed below.

3.1 The role of rotation

3.1.1 Evolution of angular momentum

One of the key necessary conditions for GRB progenitors is rapid rotation. To trigger relativistic jets, a large amount of angular momentum should be retained in the innermost layers of GRB progenitors until the pre-collapse stage. More specifically, the specific angular momentum in the core must be higher than $j > 1.5 \times 10^{16} \left(\frac{M_{\text{BH}}}{3 M_{\odot}} \right) \text{ cm}^2 \text{ s}^{-1}$ within the collapsar scenario, where M_{BH} is the black hole mass (Woosley 1993), and $j \simeq 4 \times 10^{15} \text{ cm}^2 \text{ s}^{-1}$ within the magnetar scenario (e.g., Wheeler et al. 2000).

Observations indicate that the amounts of angular momentum are sufficient to meet these criteria for a large fraction of massive main-sequence stars in the nearby universe (e.g., Mokić et al. 2006; Wolff 2006; Ramírez-Agudelo et al. 2013). Recent numerical studies also indicate that massive Pop III stars would be rapid rotators (Stacy et al. 2011; Rosen et al. 2012). However, numerous observations imply rapid transport of angular momentum inside stars (e.g., Suijs et al. 2008; Charpinet et al. 2009; Eggenberger et al. 2012; Marques et al. 2013), which must have significant impact on the final angular momentum distribution in the stellar core (Hirschi et al. 2004; Heger et al. 2005). While the main mechanism for angular momentum transport is still a matter of debate, the following two mechanisms have been considered most important in stellar evolution models.

- *Eddington-Sweet circulations*: Thermal equilibrium in rotating stars generally breaks down because the radiative flux along the polar axis becomes excessive compared to that along the equatorial one (the von Zeipel theorem; e.g., Kippenhahn & Weigert 1990). To compensate this thermal imbalance, large-scale meridional circulations are induced in rotating stars, which are nowadays often called ‘Eddington-Sweet (ES) circulations’ (e.g., Maeder & Meynet 2012). These ES circulations are not only important

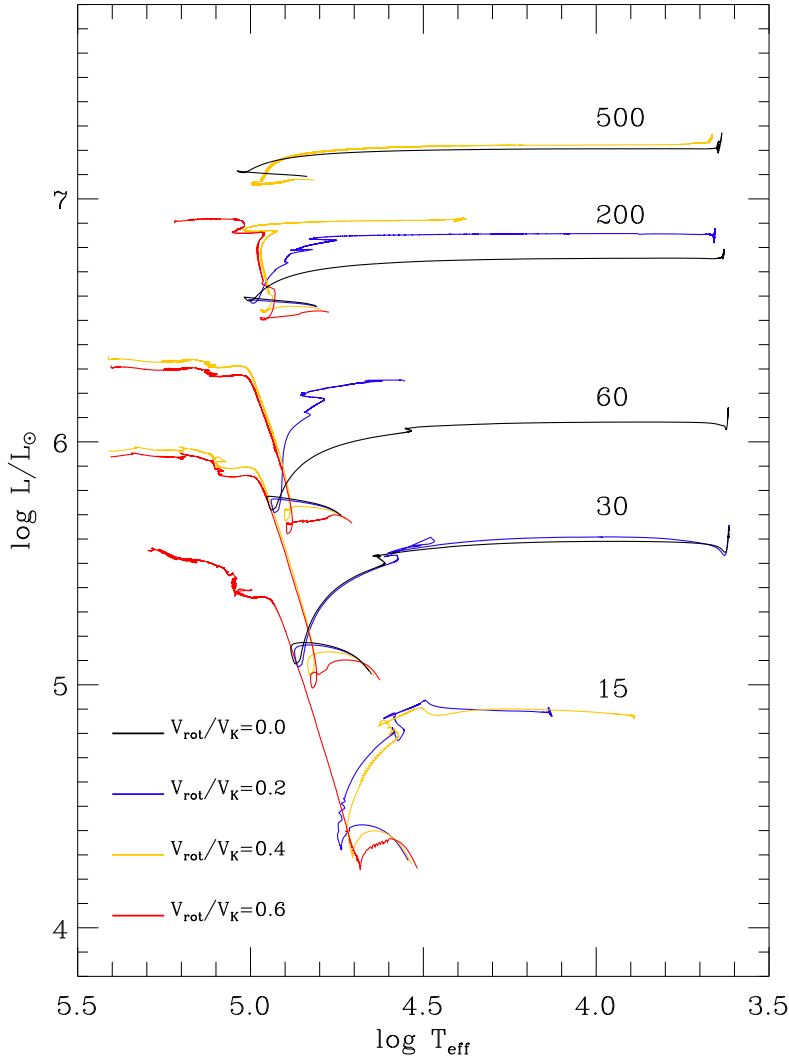


Fig. 1 Evolution of massive Pop III stars (15, 30, 60, 200 and 500 M_{\odot}) with and without rotation. The adopted initial rotational speeds in units of the Keplerian value are marked by different colors as indicated by the labels. These evolutionary models are taken from Yoon et al. (2012).

for the energy flux, but also for the transport of angular momentum. The timescale for ES circulations in a chemically homogeneous star is roughly given by $\tau_{\text{ES}} \approx \tau_{\text{KH}}(\Omega/\Omega_K)^{-2}$, where τ_{KH} denotes the Kelvin-Helmholtz timescale and Ω/Ω_K the ratio of the angular velocity to the Keplerian value. Although τ_{ES} can be in principle shorter than the nuclear timescale

- (τ_{nuc}) of a star, ES circulations are severely slowed down once the chemical stratification across the boundary between the core and the hydrogen envelope is built up (Maeder & Meynet 1998). Therefore, it is believed that ES circulations cannot efficiently brake down the stellar core for most cases (Heger et al. 2000; Hirschi et al. 2004).
- *Taylor-Spruit dynamo*: According to Taylor (1973), toroidal fields in radiative layers of stars are always unstable to create poloidal fields (see also Spruit 1999). If differential rotation can wind up thus-created poloidal fields to amplify toroidal fields, the dynamo loop can be closed (Spruit 2002). This so-called Taylor-Spruit (TS) dynamo may lead to magnetic torques that can redistribute angular momentum inside stars much more efficiently than ES circulations. Theoretical studies indeed show that solid-body rotation can be maintained in main sequence stars with TS dynamo (Heger et al. 2005). This rapid angular momentum transfer by the TS dynamo has been invoked to explain the relatively slow spin rates of young neutron stars and isolated white dwarfs, as well as angular velocity profiles in low-mass stars on various evolutionary stages that are inferred from asteroseismological data (e.g. Eggenberger et al. 2005; Heger et al. 2005; Suijs et al. 2008; Cantiello et al. 2014). However, the validity of the TS dynamo theory is still debated (e.g., Braithwaite 2006; Zahn et al. 2007; Arlt & Rüdiger 2011; Cantiello et al. 2014).

Evidently, the transport mechanisms may not be limited to these ones. Rotationally-induced hydrodynamic instabilities apart from ES circulations include the shear instability and the baroclinic instability. The interplay between ES circulations and the shear instability would be particularly important for the transport process (Maeder & Meynet 2012). Several authors also investigated the role of the magneto-rotational instability (Wheeler et al. 2015) and internal gravity waves in massive stars (Fuller et al. 2014). More progress is certainly needed to have a reliable prescription for angular momentum transport.

3.1.2 Chemical mixing

Rotationally-induced hydrodynamic instabilities can transport not only angular momentum but also chemical species. This may lead to chemical mixing of hydrogen-burning products from the convective core into the radiative envelope in a massive star on the main sequence. Enhanced abundances of nitrogen and helium are indeed found at the surfaces of many massive stars, which provide evidence for such mixing (e.g. Hunter et al. 2008, 2009). The efficiency of chemical mixing due to rotation has been recently calibrated by Brott et al. (2011) using the inferred nitrogen abundances at the surfaces of B-type stars in the Large Magellanic Cloud. But the anomalously high/low nitrogen abundances observed in some slowly/rapidly rotating stars have not been well understood yet (Hunter et al. 2008, 2009; Brott et al. 2011; Aerts 2014).

3.1.3 Mass shedding

Rapidly rotating stars can reach the critical rotation during the course of their evolution if they do not lose a sufficient amount of angular momentum via strong mass loss. Note that the critical rotation speed (v_{crit}) can become lower than the Keplerian limit ($v_K = \sqrt{GM/R}$) if the stellar luminosity approaches the Eddington limit, as the following:

$$v_{\text{crit}} = v_K \sqrt{1 - F}, \quad (1)$$

where F is the Eddington factor (Heger et al. 2000; see Maeder & Meynet 2000 for an alternative description for the critical rotation speed). Once the star reaches the critical rotation, mechanical mass shedding would occur, even when radiation-driven winds are very weak. This would be the dominant mode of mass-loss from massive Pop III stars (Marigo et al. 2003; Ekström et al. 2008; Yoon et al. 2012). For very massive stars ($M \gtrsim 100 M_\odot$), however, pulsationally driven winds during the red supergiant phase might also play an important role (Baraffe 2001; Moriya & Langer 2015).

3.2 Chemically homogeneous evolution and GRB progenitors

Typical timescales about ~ 10 secs of long GRBs imply that their progenitors are generally compact ($R \lesssim 10 R_\odot$; Woosley 2006). All of the supernovae associated with a long GRB turn out to be Type Ic, which provide further evidence for compact progenitors that have lost their hydrogen envelopes (e.g., Woosley 2006; D’Elia et al. 2015). It is therefore widely believed that the majority of long GRB progenitors are naked helium stars like Wolf-Rayet (WR) stars. Another necessary condition for long GRB progenitors is rapid rotation as mentioned above.

Mass loss by radiation-driven winds is negligible for Pop III stars, and mass shedding due to rotation is not significant enough to remove the whole hydrogen envelope (Marigo et al. 2003; Ekström et al. 2008; Yoon et al. 2012). This may raise a question of whether massive single Pop III stars can produce an ordinary long GRB.

Probably, the only possible solution for ordinary long GRBs from single Pop III stars would involve the chemically homogeneous evolution (CHE). CHE may occur with a sufficiently high rotation speed if the timescale for chemical mixing due to ES circulations becomes shorter than the nuclear timescale (Maeder 1987). In other words, CHE can be realized if rapid chemical mixing between the hydrogen-burning convective core and the radiative envelope occurs, before nuclear burning builds up a strong degree of chemical stratification across the boundary between them that would dramatically slow down ES circulations. In this case, almost all the hydrogen in the envelope of a star is mixed into the hydrogen-burning core to be fused into helium, which is

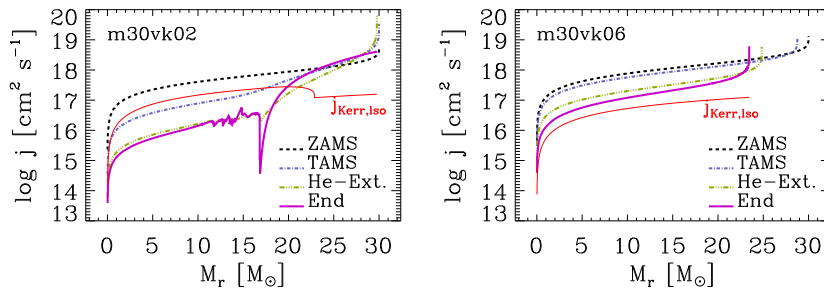


Fig. 2 Mean specific angular momentum profile as a function of the mass coordinate for different evolutionary epochs of $30 M_{\odot}$ Pop III star: zero age main sequence (ZAMS), terminal age of the main sequence (TAMS), core helium exhaustion (He-Ext.) and the last calculated model, which corresponds to core neon exhaustion. The TS dynamo was included in the calculations, and the two different initial rotational speeds were adopted: 20% and 60% Keplerian rotation speeds for the left and the right panels, respectively. In the latter case, the star evolves chemically homogeneously. Adapted from Yoon et al. (2012).

in turn mixed back into the envelope. The whole star is thus gradually transformed into a helium star by the end of the main sequence. This makes the CHE stars evolve blueward as shown in Fig. 1.

In the case of normal evolution, the helium core during the post-main sequence stage would be significantly braked down by the slowly rotating hydrogen envelope that expands to a red-supergiant phase, which can serve as a large angular momentum reservoir (Heger et al. 2005). By contrast, CHE stars do not undergo the red-supergiant phase and can retain a large fraction of the initial amount of angular momentum until the pre-collapse stage (Fig. 2; Yoon & Langer. 2005; Woosley & Heger 2006). CHE can be more easily realized at lower metallicity (Yoon et al. 2006), and therefore CHE is a promising pathway to long GRBs for massive Pop III stars (Yoon et al. 2012).

As summarized in Fig. 3 (see also Yoon et al. 2012), CHE would produce GRB progenitor candidates for the initial mass range of $13 - 84 M_{\odot}$ if the initial rotation speed is higher than about 50% of the Keplerian value. Another interesting prediction of CHE is that the initial mass range for pair-instability supernovae (PISNe) would significantly decrease to $84 - 190 M_{\odot}$, compared to the non-rotating case (i.e., $140 - 300 M_{\odot}$; see also Chatzopoulos & Wheeler 2012). These PISNe from CHE stars would appear as Type Ic, instead of Type IIP that is expected for non-rotating or slowly rotating PISN progenitors. For the initial mass range of $56 - 84 M_{\odot}$ of GRB progenitors, a pulsational PISN would occur shortly before the core collapses into a black hole, which may produce a very bright optical event via an interaction between the pulsational PISN ejecta and the GRB jet that follows.

3.3 Supergiant Pop III progenitors for ultra-long GRBs

With relatively slow rotation, the typical core-envelope structure is developed in a massive Pop III star after the end of core hydrogen burning. The helium

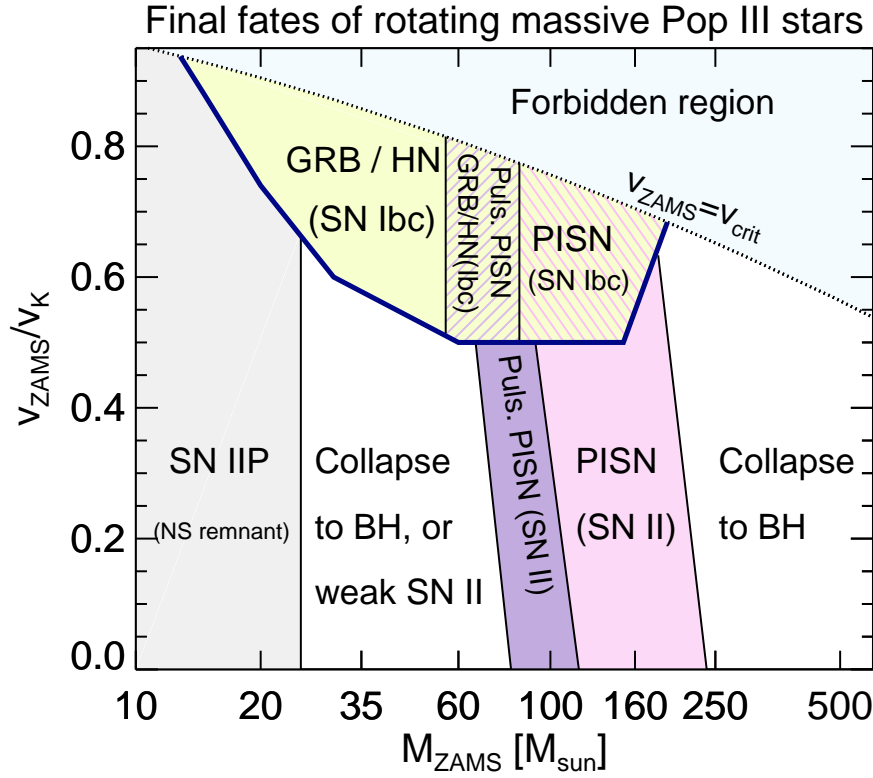


Fig. 3 Final fates of rotating massive Pop III stars, in terms of the initial mass and the initial rotational speed in units of the Keplerian value. The boundary for the CHE regime is marked by the thick solid line. The dotted line denotes the critical rotational speed for a given ZAMS mass, as defined by Eq. (3.1.3). This figure is a reproduction of Figure 12 in Yoon et al. (2012) with permission from Astronomy & Astrophysics, © ESO.

core is expected to be spun down as the core angular momentum is transferred to the expanding hydrogen envelope. At the pre-collapse stage, the inner core would rotate relatively slowly and its specific angular momentum would not exceed the critical limit for producing a GRB.

Interestingly, because Pop III stars do not lose much mass, the total angular momentum can be more or less conserved and the specific angular momentum of the hydrogen envelope increases as a result of the angular momentum transfer from the core (see the left panel of Fig 2). In this case, the core would directly collapse into a BH, and the envelope material would form a Keplerian disk around it. The consequent accretion rate depends on the free-fall time of the envelope material: it would be $\sim 10^{-4} M_{\odot} \text{ yr}^{-1}$ for a blue-supergiant (BSG) progenitor, and $\sim 10^{-6} M_{\odot} \text{ yr}^{-1}$ for a red-supergiant (RSG) progenitor (Woosley & Heger 2012). Therefore, supergiant Pop III stars could produce an ultra-long GRB having a timescale of $10^3 - 10^7$ sec (cf. Gendre et al. 2013;

Virgili 2013; Evans et al. 2014; Levan 2014; Piro et al. 2014), depending on the final structure (Suwa & Ioka 2011; Nakauchi et al. 2012; Woosley & Heger 2012; Yoon et al. 2015).

Note, however, that the hydrogen envelope of a RSG is very loosely bound. Recently, Lovegrove & Woosley (2013) showed that most of the RSG envelope may be ejected as a result of the rapid loss of gravitational mass due to neutrino emission from the core while a BH is formed. This makes it difficult for a RSG to produce a long GRB transient even if its envelope is rotating rapidly. By contrast, the binding energy of a BSG envelope is fairly high and it would remain gravitationally bound to the newly formed BH. Therefore, rapidly rotating BSGs should be considered good progenitor candidates for ultra-long GRBs with a timescale of about $10^3 - 10^4$ sec (Woosley & Heger 2012).

The remaining question is whether massive Pop III BH progenitors end their lives as a BSG or a RSG. Although the relatively low-opacity with zero-metallicity helps a massive Pop III star remain compact, non-linear effects of stellar evolution make it very difficult to make a robust prediction on the final structure. For example, lower opacity in the core of a Pop III star than in a metal-rich counterpart leads to a smaller size of the convective core on the main sequence for a given mass, which in turn results in a more compact carbon-oxygen core at the end of core helium burning. As a consequence, the helium-burning shell source becomes very hot, inducing a more violent convection above it. This often leads to penetration of the convection zone of the helium shell source into the hydrogen-burning shell, boosting the CNO cycle (Heger & Woosley 2010; Limongi & Chieffi 2012; Yoon et al. 2012). The huge amount of nuclear energy produced in this way can make the star become a RSG shortly before core collapse. The onset of this CNO boosting sensitively depends on the adopted overshooting parameter and the initial rotation speed, but it is usually found for Pop III stars in the mass range of about $10 - 30 M_{\odot}$ (C. Kye & S.-C. Yoon in prep). For more massive Pop III stars, the RSG solution seems to be generally favored (Marigo et al. 2001, 2003; Ekström et al. 2008; Yoon et al. 2012), but for a limited mass range of about $30 - 60 M_{\odot}$, the BSG solution could be obtained with moderate rotation or weak overshooting (Limongi & Chieffi 2012; Yoon et al. 2012; C. Kye & S.-C. Yoon in prep; see also Fig. 1).

3.4 Very massive Pop III stars and supercollapsars

For the mass range above the PISN limit and below the general relativistic instability limit (e.g., $260 M_{\odot} \lesssim M \lesssim 50000 M_{\odot}$ without rotation), Pop III stars would directly collapse to a BH with $M \gtrsim 100 M_{\odot}$ (e.g., Fryer et al. 2001). This would lead to a collapsar that may produce a long GRB having a very high total energy ($\gtrsim 10^{53} - 10^{54}$ erg) and a very long timescale ($T \sim 10^4 - 10^6$ sec), depending on the final structure of the progenitor star (the so-called supercollapsar; Komissarov & Barkov 2010; Mészáros & Rees 2010).

In terms of stellar evolution, the following issues should be considered to probe the possibility of Pop III supercollapsars.

- Very massive stars are close to the Eddington limit, and can reach the critical rotation at a relatively low rotation speed. Angular momentum loss through mass shedding becomes significant accordingly, which slows down ES circulations. For this reason, CHE cannot be easily realized for very massive Pop III stars with $M \gtrsim 200 M_{\odot}$ (Yoon et al. 2012). This means that they would not be able to avoid developing the typical core-envelope structure during the post-main sequence phase.
- The angular momentum transport from the core to the envelope can easily remove the core angular momentum in this case, if there exists a strong coupling between them via, for example, magnetic torques. The angular momentum condition for a collapsar cannot be fulfilled in this case (Yoon et al. 2012). By contrast, if ES circulations were the dominant mode of angular momentum transfer, the core and/or the envelope would retain a sufficient amount of angular momentum to produce a collapsar for a limited mass range of about $300 M_{\odot} \lesssim M \lesssim 700 M_{\odot}$ (Yoon et al. 2015).
- The RSG solution is strongly favored for these very massive stars: it is most likely that Pop III stars with $M > 260 M_{\odot}$ end their lives as a RSG (Marigo et al. 2003; Yoon et al. 2012, 2015). Therefore, even if the core was rotating rapidly enough to produce a collapsar, the resultant relativistic jet would not be able to penetrate the envelope. The final outcome would be a jet-driven Type IIP supernova, rather than a GRB. The caveat here is that the mass loss rate from such a very massive RSG is not well understood. RSG stars are usually unstable to radial pulsations, and pulsation-driven winds might be significant. Whether or not such winds can completely remove the hydrogen envelope of a very massive Pop III RSG star is a matter of debate (e.g., Baraffe 2001; Moriya & Langer 2015).
- For a supercollapsar, a neutrino-driven jet cannot be efficient because of the large radius of the last stable orbit around such a massive black hole. Therefore, another important ingredient for a successful supercollapsar is strong large-scale magnetic fields in the progenitor star such that a relativistic jet may be triggered via the Blandford-Znajek (BZ) mechanism (Komissarov & Barkov 2010; Mészáros & Rees 2010, see also Section 4). Magnetic field configuration in massive stars at the pre-collapse stage has been hardly investigated so far, and we still do not know if this condition of strong large-scale magnetic fields can be fulfilled in very massive Pop III stars.

In short, a supercollapsar seems to be rather difficult to produce from very massive Pop III single stars, given that they would not follow CHE and that they would become a RSG at the pre-collapse stage, rather than a BSG or a naked He star. However, binary interactions might produce a BSG supercollapsar progenitor more easily, as discussed in Sect. 3.5 below.

3.5 Binary interactions and GRB progenitors

Binary interactions would be an alternative way to produce naked helium stars at zero metallicity. However, it is expected that they are slow rotators in general and would not produce a GRB (Yoon et al. 2010): GRB production even from binary stars would require an exotic evolutionary path. Several different scenarios for binary GRB progenitors have been suggested (see Brown et al. 2000; Izzard et al. 2004; Fryer & Heger 2005; van den Heuvel & Yoon 2007; Podsiadlowski et al. 2010), but because of the complexity of the related physical processes like common envelope ejection, the details of these scenarios have not been properly investigated with self-consistent binary evolution models for most cases.

Here we summarize the possibly important aspects of binary stars for Pop III GRBs, which should be carefully studied in the near future.

- Mass exchange in close binary systems can enhance the number fraction of rapidly rotating stars (de Mink et al. 2013). As shown by Cantiello et al. (2007), the Case B mass transfer (i.e., mass transfer during the helium core contraction phase or the early stage of core helium burning) is likely to enhance the possibility for CHE in mass accretors. The parameter space for this solution should be systematically explored for Pop III binaries.
- In the literature, evolutionary channels including the Case C mass transfer (i.e., mass transfer during the late stage of core helium burning or thereafter) has been often invoked to explain GRB progenitors (Brown et al. 2000; van den Heuvel & Yoon 2007; Podsiadlowski et al. 2010). In metal-rich environments, strong mass loss tends to prohibit the Case C mass transfer from massive stars with $M > 30 M_{\odot}$ that are potential BH progenitors, but it would occur more frequently for Pop III stars that do not lose much mass. It is therefore possible that the Case C channel for long GRBs would be more important for Pop III stars than in the nearby universe.
- Binary mergers (in particular Case B mergers) may produce a BSG progenitor more easily, because a fairly small mass ratio of the helium core to the hydrogen envelope can be achieved in the merger remnants (e.g., Justham et al. 2014). Although the helium core may not be necessarily rapidly rotating in this case, the hydrogen envelope must have a very high specific angular momentum until the pre-collapse stage because mass loss from Pop III stars is weak. Therefore, Case B mergers at low-metallicity would be a very promising pathway to ultra-long GRBs. It would be particularly interesting if very massive BSG GRB progenitors ($M \gtrsim 300 M_{\odot}$) could be produced in this way (see Yoon et al. 2015, for a more detailed discussion).

4 Observational signatures in Pop III GRBs

4.1 How to identify Pop III GRBs?

Recent studies on stellar formation in the early universe predict that Pop III stars may be most prominent at $z \sim 20 - 30$ (e.g. Abel et al. 2002; Yoshida et al. 2008; Bromm & Yoshida 2011, and see Sections 1 and 2). Observations of GRBs may provide unique probes of the physical conditions of the universe at such redshifts. Due to their high luminosities, GRB prompt emissions and afterglows are expected to be observable at least out to $z \gtrsim 10$ (e.g. Lamb & Reichart 2000; Ciardi & Loeb 2000; Bromm & Loeb 2002; Yonetoku et al. 2004; Gou et al. 2004). This can serve as a tracer of the history of the cosmic star formation rate (Totani 1997; Porciani & Madau 2001; Bromm & Loeb 2006; Kistler et al. 2009; de Souza et al. 2011) and provide invaluable information on the physical conditions in the intergalactic medium (Barkana & Loeb 2004; Ioka & Mészáros 2005; Inoue 2007). Currently, the most distant GRB that has been spectroscopically confirmed is GRB 090423 at $z \simeq 8.2$ (Tanvir et al. 2009; Salvaterra et al. 2009), and GRB 090429B has a photometric redshift $z \simeq 9.4$ (Cucchiara et al. 2011). The detailed spectroscopic observation of GRB 050904 at $z \simeq 6.3$ has put a unique upper bound on the neutral hydrogen fraction in the intergalactic medium at that redshift and estimated the metallicity (Totani et al. 2006; Kawai et al. 2006). See also a recent detailed analysis of GRB 130606A at $z \simeq 5.9$ and related debates (Totani et al. 2015, and references therein). These observations indicate that GRBs are very promising for exploring the high-redshift universe (for a recent review, see Salvaterra 2015).

In the context of the study of Pop III stars, a crucial question is how can we identify GRBs originating from Pop III stars (Pop III GRBs) among bursts whose redshifts are determined as $z \gtrsim 10$ e.g. by observation of the Ly α cutoff at the IR frequencies. An unambiguous way to pinpoint a Pop III progenitor is to examine whether the afterglow spectrum from its surrounding medium is devoid of iron-group elements¹ through high-resolution IR and X-ray spectroscopy by ground-based facilities and/or future space experiments. However, there may also be the case that the surrounding medium is embedded in a region where stellar explosions have already occurred slightly earlier, and the absorption lines of the first heavy elements produced by those explosions are thus imprinted (Wang et al. 2012). A true Pop III origin of the GRB progenitor could then be missed due to this masquerading effect. It is therefore important to explore alternative strategies to identify Pop III GRBs. In this regard, another proposed way is to focus on the total energies and durations of GRBs estimated by the X-ray and gamma-ray observations of prompt emissions and/or afterglows (Komissarov & Barkov 2010; Mészáros & Rees 2010; Toma et al. 2011; Suwa & Ioka 2011). Pop III stars could be very massive stars

¹ It may be misleading to state “devoid of metals”. Pop III GRB progenitors via CHE, for example, could have ejected CNO elements into the surrounding medium via mass shedding during the late stages of their evolution.

(VMSs) with $M \gtrsim 300M_\odot$, and then GRBs originating from Pop III VMSs (Pop III VMS GRBs) could have peculiarly large total energies and long durations.² Their values could be orders of magnitude larger than those of ordinary Pop I and Pop II GRBs, providing strong hints for Pop III progenitors.

The recent numerical studies of the evolutions of Pop III stars imply that luminous GRBs are rather difficult to occur from VMSs (Yoon et al. 2012, 2015), as discussed in Section 3. However, it may not be interpreted as a robust prediction yet, since theoretical modelings of formation and evolution of Pop III stars are highly non-linear, complex problems, as also noted in Section 3. There are several factors to be investigated, such as the multi-dimensional effects related to magnetic field and stellar rotation, the radiative feedback, the mass accretion after the onset of core hydrogen burning, the binary interactions, and so on. If only Pop III stars with $M < 100M_\odot$ could produce GRBs, it would not be simple to identify Pop III GRBs through the estimate of the total energy and duration scales. Such bursts at the high redshifts may not be detectable by the current satellites (Nakauchi et al. 2012), and then persistent efforts on observational and theoretical studies with new high-sensitivity satellites would be needed to find out possible statistical differences between Pop III GRBs and ordinary GRBs. On the other hand, the history of GRB study tells us that some breakthroughs happened by simple observations, such as the serendipitous discovery of GRBs itself, the isotropic angular distribution of GRBs in the sky revealed by BATSE, the discovery of the afterglow by Beppo-SAX, the confirmation of the connection between GRBs and supernovae by HETE-2, and several recent discoveries by Swift and Fermi (for reviews, see e.g. Zhang & Mészáros 2004; Kumar & Zhang 2015). The connection between GRBs and Pop III stars might also be discovered by a serendipitous observation of a source which looks peculiar. Here we consider a case in which Pop III VMSs can produce GRBs as luminous as ordinary GRBs and discuss their unique observational signatures. Searches of such peculiar GRBs will constrain the theoretical models of the formation and evolution of Pop III stars.

4.2 Pop III VMS GRB model

Let us first make a phenomenological interpretation of the total gamma-ray energies and durations of ordinary long GRBs which are currently observed. Focusing on the most energetic GRBs, which are mainly detected by Fermi satellite, they have $E_{\gamma,iso} \sim 10^{54} - 10^{55}$ erg. The typical duration is $T \sim 10 - 100$ s (Ackermann et al. 2013). In the collapsar model, the total gamma-ray energy can be written as

$$E_{\gamma,iso} = \frac{\epsilon_\gamma \eta M_{acc} c^2}{1 - \cos \theta_j} \sim 6 \times 10^{54} \epsilon_\gamma \left(\frac{\eta}{10^{-2}} \right) \left(\frac{M_{acc}}{M_\odot} \right) \left(\frac{\theta_j}{0.1} \right)^{-2} \text{ erg}, \quad (2)$$

² Recently, GRBs from supermassive stars with $M \sim 10^5 M_\odot$ which could make seed BHs for supermassive BHs are also discussed (Matsumoto et al. 2015).

where ϵ_γ is the gamma-ray radiation efficiency, η the conversion factor from the accretion energy to the jet energy, M_{acc} the total mass accreted by the central black hole (BH), and θ_j the opening half angle of the jet. While $\epsilon_\gamma \gtrsim 0.5$ and $\theta_j \sim 0.1$ are supported by some observational indications (Ioka et al. 2006; Zhang et al. 2007; Frail et al. 2001) (but see Beniamini et al. 2015), the values of η and M_{acc} are highly uncertain. (Furthermore, the conversion factor from the accretion luminosity $\dot{M}_{\text{acc}}c^2$ to the jet luminosity may be time-dependent, so that η in equation (2) should be interpreted as a rough temporally-averaged value of the energy conversion factor.) In a scenario in which the progenitor star has an initial mass $\sim 30 M_\odot$, ends its life as a Wolf-Rayet star of $\sim 15 M_\odot$ after losing a large fraction of mass by the stellar wind, and collapses making a BH of $\sim 3 M_\odot$, being accompanied by a supernova explosion with an ejecta mass of $\sim 10 M_\odot$ (Iwamoto et al. 1998; Mazzali et al. 2006), the total accreted mass is $M_{\text{acc}} \sim M_\odot$. If the stellar wind is so weak that the star does not lose much of its mass, we have $M_{\text{acc}} \sim 10 M_\odot$. Correspondingly, η can be estimated to be $\sim 10^{-4} - 10^{-2}$ for $E_{\gamma, \text{iso}} \sim 10^{54} - 10^{55}$ erg.

The conversion factor η should be determined by the jet production mechanism. For driving relativistic jets, the thermal energy injection by $\nu\bar{\nu}$ annihilation (Eichler et al. 1989) and/or the electromagnetic energy injection by magnetic braking of the accretion disk or the BH may be viable. In the former thermal model, η is estimated to be $\sim 10^{-4} - 10^{-2}$ for $\dot{M}_{\text{acc}} \sim (0.1 - 1) \times M_\odot \text{ s}^{-1}$ and $M_{\text{BH}} = 3 M_\odot$ (Zalamea & Beloborodov 2011). However, it depends on the condition of the BH accretion such as the strength of the disk wind (see also Suwa 2013). In the latter magnetic model, BZ process, i.e. the magnetic braking of the BH or the energy extraction of the BH rotational energy (Blandford & Znajek 1977), can give rise to even $\eta > 1$ as demonstrated by MHD numerical simulations (Tchekhovskoy et al. 2011). There have been some observational indications supporting such a high value of η in relativistic jets of active galactic nuclei (e.g. Fernandes et al. 2011; Ghisellini et al. 2014). In this model also, η depends on the condition of the BH accretion as well as on the behavior of the magnetic field (e.g. Tchekhovskoy & Giannios 2015). There are also some issues relating to the physics of the BZ process itself (Komissarov 2009; Toma & Takahara 2014).

The total duration scale may be estimated as the disk lifetime. If the progenitor star is rotating at half of the break-up speed, then the initial outer edge of the disk is at $R_d \simeq R/4$, where R is the stellar radius. The disk lifetime is given by its viscous accretion timescale $\sim R_d^2/(\alpha c_s H)$, where α is the effective viscous stress parameter of the α -disk model (Shakura & Sunyaev 1973), c_s the sound speed, and H the scale height of the disk. The balance equation between the thermal pressure gradient and the gravitational force gives $c_s/H \sim \Omega_K$, where Ω_K is the Keplerian angular velocity, so that we have in the thick disk case ($H \sim R_d$)

$$T \sim \frac{1}{\alpha \Omega_K} (1+z) \simeq 200 \left(\frac{\alpha}{0.1} \right)^{-1} \left(\frac{R}{10^{10} \text{ cm}} \right)^{\frac{3}{2}} \left(\frac{M_{\text{BH}}}{3M_\odot} \right)^{-\frac{1}{2}} \left(\frac{1+z}{3} \right) \text{ s.} \quad (3)$$

We should note that the duration of the bright part of the prompt emission may be shorter than this estimate since the conversion factor from the accretion luminosity to the jet luminosity and the accretion luminosity itself are time-dependent (Komissarov & Barkov 2010; Kumar et al. 2008; Tchekhovskoy & Giannios 2015).³

We apply the above scalings of the total gamma-ray energy and duration to a VMS progenitor with $M_* \sim 10^3 M_\odot$, although those scalings include many uncertainties. If we substitute $M_{\text{acc}} \sim 300 M_\odot$, $M_{\text{BH}} \sim 300 M_\odot$, $R \sim 10^{12}$ cm, and $z \sim 20$ for equations (2) and (3), we obtain

$$E_{\gamma, \text{iso}} \sim 10^{57} \left(\frac{\eta}{10^{-2}} \right) \text{ erg}, \quad T \sim 1 \text{ day}. \quad (4)$$

Therefore, if we were to observe a burst at redshift $z \gtrsim 10$ with such large $E_{\gamma, \text{iso}}$ and T , this would very likely be a Pop III VMS GRB (Mészáros & Rees 2010; Toma et al. 2011).

For such large BH masses, the density and temperature of the accretion disk are too low for neutrino cooling to be important, and then the thermal energy from the $\nu\bar{\nu}$ annihilation is insufficient to power strong jets (Fryer et al. 2001; Komissarov & Barkov 2010; Zalamea & Beloborodov 2011). The electromagnetic effects such as BZ process may instead power the jets, which should be dominated by Poynting flux (see also Suwa et al. 2007).

Pop III VMS GRBs share the property of the extremely long durations with Ultra-long GRBs, which were recently detected by Swift with low redshifts (e.g. Gendre et al. 2013; Levan 2014). Ultra-long GRBs have durations as long as $T \sim 10^4$ s, although their total gamma-ray energies are $E_{\gamma, \text{iso}} \sim 10^{53} - 10^{54}$ erg, which are comparable to those of ordinary GRBs. Thus the property of the extremely high $E_{\gamma, \text{iso}}$ would still be a unique property of Pop III VMS GRBs.

Given the propagation speed of the Poynting flux dominated jet inside the progenitor star, $\sim 0.2c$, deduced from MHD simulations (Barkov & Komissarov 2008; Bromberg & Tchekhovskoy 2015), the intrinsic duration of Pop III VMS GRBs $T/(1+z) \sim 10^4$ s is sufficient to break through the star (see also Mészáros & Rees 2001). Suwa & Ioka (2011) performed a semi-analytic calculation of the jet propagation inside the star with $R \sim 10^{13}$ cm, which is an order of magnitude larger than our assumption, and showed that the jets can successfully break through the star (see also Nagakura et al. 2012). While the jet is propagating inside the star, the energy of the jet is dissipated at the jet head and makes a thermally dominated cocoon between the jet and the stellar envelope (Begelman & Cioffi 1989; Mészáros & Rees 2001; Matzner 2003; Bromberg et al. 2011; Bromberg & Tchekhovskoy 2015). The cocoon can also be ejected after the jet breakout, and it can release thermal emission, which provide information about the progenitor star (Kashiyama et al. 2013). Indeed, the luminous supernova-like emission associated with Ultra-long GRB

³ Mizuta & Ioka (2013) propose an alternative scenario that the duration of the bright part of the prompt emission is determined by an increase of θ_j on a timescale of the pressure decay of the cocoon emerging from the progenitor star.

111209A can be explained by the cocoon thermal emission (Nakauchi et al. 2013) (but see Greiner et al. 2015).

4.3 Prompt emission

We may roughly estimate the isotropic gamma-ray luminosity from equations (2) and (3) by $\sim E_{\gamma,iso}/[T/(1+z)]$ as

$$L_{\gamma,iso} \sim 3 \times 10^{53} \epsilon_{\gamma} \eta_{-2} \alpha_{-1} \theta_{j,-1} R_{12}^{-\frac{3}{2}} \left(\frac{M_{acc}}{300 M_{\odot}} \right) \left(\frac{M_{BH}}{300 M_{\odot}} \right)^{\frac{1}{2}} \text{ erg s}^{-1}, \quad (5)$$

where the notation $Q_x = Q/10^x$ in cgs units is adopted. This value is only one order of magnitude larger than that of ordinary GRBs.

We require the spectral model to examine the detectability of the prompt emission of Pop III VMS GRBs, although the prompt emission mechanism of GRBs is still under debate. Particularly for the magnetically dominated jets, it is very uncertain.

Even the magnetically dominated jets may have a subdominant thermal component, which may be released at the photosphere of the jets. The spectrum of this thermal emission can be estimated in a standard fireball model (Toma et al. 2011). For the photospheric thermal luminosity as $3 \times 10^{52} \text{ erg s}^{-1}$ and $1+z = 20$, the spectral peak energy and the flux are estimated as $E_{p,obs} \simeq 70 \text{ keV}$ and $F \simeq 7 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1}$. This emission is marginally detectable by the BAT detector on Swift.

An alternative way to estimate the spectral peak energy of the prompt emission is based on empirical laws claimed for observed ordinary GRBs (Nakauchi et al. 2012). If the Poynting flux of the jets are efficiently converted to the radiation energy flux, the observed flux is $F \sim 7 \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}$ for $L_{\gamma,iso} \sim 3 \times 10^{53} \text{ erg s}^{-1}$ and $1+z = 20$. Then if the spectral property obeys the empirical $E_p - L_{\gamma,iso}$ relation (Yonetoku et al. 2010), we have $E_{p,obs} \sim 80 \text{ keV}$, or if the spectral property obeys the empirical $E_p - E_{\gamma,iso}$ relation (Amati 2006), we have $E_{p,obs} \sim 4 \text{ MeV}$. In both cases the prompt emission is detectable by currently operating satellites.

However, we have adopted $\eta \sim 10^{-2}$ for the above estimates, which correspond to the high end of the estimate of η (see Section 4.2). For conservative values $\eta \sim 10^{-4} - 10^{-3}$, the radiation luminosity is orders of magnitude smaller, so that their detections by the current satellites are difficult. Next-generation satellites will be needed in such cases (Suwa & Ioka 2011; Nakauchi et al. 2012).

4.4 Afterglow

The external shock driven by the jet in the circumburst medium powers the afterglow, which can be studied independently of the prompt emission (Mészáros & Rees 1997; Sari et al. 1998). The external shock amplifies the

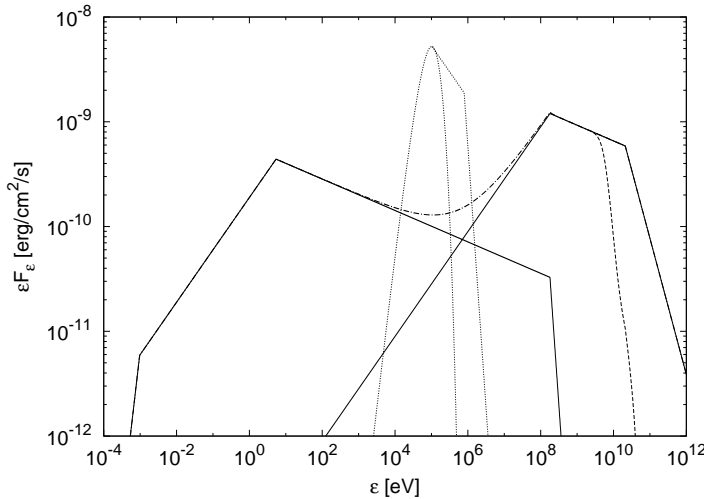


Fig. 4 Example of the spectrum of a Pop III VMS GRB at the time when the jet activity ends. The physical parameters are $E_{iso} = 4 \times 10^{57}$ erg, $T = 2.3$ day, $1 + z = 20$, $n = 1 \text{ cm}^{-3}$, $\epsilon_B = 10^{-2}$, $\epsilon_e = 10^{-1}$, and $p = 2.3$. The dot-dashed line is the external shock spectrum, which consists of the synchrotron and SSC components (solid lines). The absorption due to extragalactic background light is expected to become significant above 7 GeV, as shown by the dashed line. The dotted line represents the prompt emission as a subdominant photospheric thermal component. See Toma et al. (2011) for more details.

magnetic field in the shocked region via plasma and/or magnetohydrodynamic instabilities and accelerates the electrons in the shocked region to a power-law energy distribution. The accelerated electrons produce synchrotron and synchrotron-self-Compton (SSC) radiation as an afterglow. This afterglow model seems to be robust, since it can explain many of the late-time (i.e. since several hours after the burst trigger) multi-band afterglows so far, and simple extension of this model (e.g. continuous energy injection into the external shock) may explain many of the early-time afterglows (Liang et al. 2007).

Calculations of the external shock emission spectrum involve the parameters E_{iso} (i.e. the total jet energy minus $E_{\gamma, iso}$), the number density n of the circumburst medium, the fractions ϵ_B and ϵ_e of the thermal energy in the shocked region that are carried by the magnetic field and the accelerated electrons, respectively, and the index p of the energy spectrum of the accelerated electrons. The latter three microphysical parameters have been constrained by model-fitting the late-time afterglows as $10^{-5} \lesssim \epsilon_B \lesssim 10^{-1}$, $\epsilon_e \sim 10^{-1}$, and $p \sim 2.3$ (e.g. Panaitescu & Kumar 2002; Wijers & Galama 1999).

Figure 4 is an afterglow spectrum at the time $t \sim T$ from the burst trigger (i.e. the early brightest phase of the afterglow) calculated for Pop III VMS GRBs by Toma et al. (2011). The parameters are $E_{iso} = 4 \times 10^{57}$ erg, $T = 2.3$ day, $1 + z = 20$, $n = 1 \text{ cm}^{-3}$, $\epsilon_B = 10^{-2}$, $\epsilon_e = 10^{-1}$, and $p = 2.3$. We found that the flux at the IR frequency is sufficient to estimate the redshift.

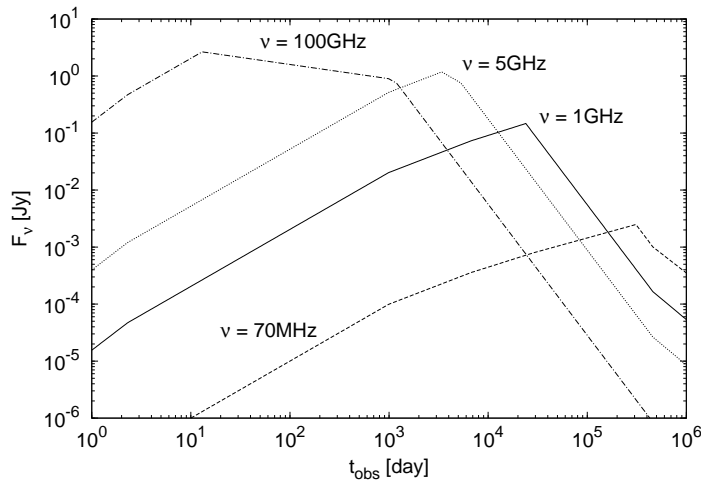


Fig. 5 Radio light curves at frequencies, 100 GHz, 5 GHz, 1 GHz, 70 MHz, of a Pop III VMS GRB at $1 + z = 20$ with the same physical parameters as Figure 4. See Toma et al. (2011) for more details.

(Macpherson et al. (2013) discuss the afterglow detectability with JWST and SPICA more systematically for broad range of parameters.) The Swift XRT and Fermi LAT can detect the X-ray and gamma-ray radiation of this afterglow, which may constrain the total energy scale E_{iso} and the number density n of the circumburst medium. The constraint on n would provide invaluable information about the environment and the radiation feedback of Pop III VMSs at the phase prior to their explosions (Kitayama et al. 2004; Whalen et al. 2004; Wang et al. 2012). A caveat is that in order to perform X-ray observation, one of the wide-field detectors, e.g. Swift BAT and Fermi LAT, has to be triggered by the prompt emission or the afterglow itself.

Toma et al. (2011) also found that the afterglows in the radio band are so bright that they might be detected by survey observations with current radio telescopes. Figure 5 is the light curves at various radio frequencies of the afterglow with the same physical parameters as Figure 4. This shows that the radio afterglows of Pop III VMS GRBs can be very bright with very long durations. These may be point sources with very long variability times in the radio sky. Deep radio surveys might detect them or can constrain the rate of the Pop III VMS GRBs (Toma et al. 2011; de Souza et al. 2011; Ghirlanda et al. 2013; Macpherson & Coward 2015). Furthermore, such bright radio sources could be useful for 21 cm absorption line searches (Furlanetto & Loeb 2002; Ioka & Mészáros 2005; Toma et al. 2011; Ciardi et al. 2015), although we should note that the brightness of the afterglow highly depends on the uncertain parameters discussed in Section 4.2, similarly to the prompt emission.

The external shock can also accelerate protons to the non-thermal energy distribution, which can produce high-energy neutrinos via $p\gamma$ interaction. The

flux of these neutrinos can be high in the 10–100 PeV energy range (Gao et al. 2011) (see also Berezhinsky & Blasi 2012).

5 Outlook

What then are the prospects for probing the end of the cosmic dark ages with GRBs, and what are key challenges ahead? For the time being, the *Swift* satellite, with its on-board X-ray and optical telescopes for the rapid localization of gamma-ray transients in the sky, will remain a good facility for catching high-redshift GRBs with $z \gtrsim 6 - 9$. The next mission, SVOM, with similar capabilities as *Swift*, is now being prepared to follow it. Several other satellite missions targeting higher-redshift GRBs, such as JANUS and Lobster, have also been proposed. Increasing the statistics of high-redshift GRBs, and detecting peculiar sources suggestive of VMS progenitors, will constrain theories of the formation and evolution of Pop III stars, and their GRB production mechanism, as discussed in this article. Wide-field, space-based gamma-ray/X-ray detectors are required to keep operating not only for high-redshift observations but also for upcoming gravitational wave astronomy, which requires electromagnetic counterparts for robust confirmation. The deep surveys in the radio wavelengths may also be helpful for Pop III GRB searches.

From the theory side, we cannot yet make any robust predictions for the final masses (i.e., the IMF), radii, rotation speeds, magnetic field strengths and its configurations, and the binarity of Pop III stars either at the time of formation or at the final evolution stage before the explosion. Similarly, during the GRB explosion phase, the mechanisms of driving relativistic jets and releasing high-energy emissions are still subject to considerable uncertainty. However, numerical simulations have been steadily extending our understanding of some of those ingredients, and they will keep playing a crucial role in theoretical study.

It is clearly important to improve our understanding of the Pop III GRB formation channel, in particular regarding the rotation state of the progenitor stars, and the characteristics of tight binaries. The challenge here is two-fold. We need simulations with even higher resolution, to push into the regime of possible binary overflow phenomena (Roche-lobe and common envelope), while maintaining the large-scale cosmological boundary conditions. The second challenge is improved physics, in particular inclusion of magnetohydrodynamic effects. The latter may crucially impact both the fragmentation properties of the primordial gas, and the rotation rates of the resulting Pop III stars.

The effects of rotation, magnetic fields and binary interactions are also critical in the evolution of Pop III GRB progenitor stars. Furthermore, the rapid rotation and strong magnetic field are key ingredients for producing relativistic jets via the BZ process. Our understanding of these physical processes in massive star evolutions has been greatly improved during the last decade both observationally and theoretically, but uncertainties regarding the

transport processes of angular momentum and chemical species inside stars still remain large. In particular, we still lack direct observations of very metal poor massive stars, which makes it difficult to test stellar evolution theory of massive Pop III stars. We hope to overcome this difficulty with systematic studies on massive star populations in very metal poor environments like in I Zwicky 18 (e.g. Szécsi et al. 2015).

Another key uncertainty relates to theoretical predictions for the rate of Pop III bursts. Even if we can narrow down the uncertainty in the Pop III GRB formation efficiency, as outlined in the previous paragraph, we still have to contend with the poorly constrained Pop III star formation rate density. This rate is only known within 2 to 3 orders of magnitude, mostly because of our incomplete understanding of the (radiative and SN) feedback effects that regulate the primordial star formation process. Again, improved cosmological simulations with ever more realistic feedback implementations promise to provide more robust determinations in the next few years. To give a rough ballpark impression of current, state-of-the-art predictions for the Pop III GRB rate at $z \gtrsim 6$: a robust upper limit should be $\sim 10 \text{ yr}^{-1} \text{ sr}^{-1}$ (Salvaterra et al. 2011), and a more realistic limit may be $0.1 \text{ yr}^{-1} \text{ sr}^{-1}$ (Campisi et al. 2011). Again, the hope is that progress in our understanding of both the Pop III GRB progenitor physics and the global star formation rate density is achievable in the near future.

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